

## DIFFUSE FAR-ULTRAVIOLET OBSERVATION OF THE LUPUS LOOP REGION

JONG-HO SHINN<sup>1</sup>, KYOUNG WOOK MIN<sup>1</sup>, CHI-NA LEE<sup>1</sup>, JERRY EDELSTEIN<sup>2</sup>, ERIC J. KORPELA<sup>2</sup>, BARRY Y. WELSH<sup>2</sup>,  
 WONYONG HAN<sup>3</sup>, UK-WON NAM<sup>3</sup>, HO JIN<sup>3</sup>, DAE-HEE LEE<sup>3</sup>

*Draft version February 5, 2008*

### ABSTRACT

Diffuse far-ultraviolet (FUV) emissions from the Lupus Loop region (SNR 330.0+15.0) have been observed with *Spectroscopy of Plasma Evolution from Astrophysical Radiation (SPEAR)*, also known as *Far-ultraviolet IMaging Spectrograph (FIMS)*. We have detected several important ionic lines, including Si II\*, C IV, and N IV], which characterize the warm, hot ionized gas in this region. The spatial variations in the line intensities of Si II\* and C IV have also been studied in comparison with X-ray and dust observations. The result shows that they originate from the interface between the hot gas seen in the X-ray and the cooler H I shell with which dust is associated. The interface is rather diffuse, and the gases with different temperatures seem to co-exist in this region. A shock may exist upfront in the interface, but its velocity should be very small as no shock-related distinguished feature is seen in H $\alpha$ .

*Subject headings:* ISM: individual (Lupus Loop) — supernova remnants — ISM: clouds — ISM: bubbles — ISM: evolution

### 1. INTRODUCTION

The Lupus Loop (SNR 330.0+15.0) is a large non-thermal radio source ( $\phi \sim 270'$ ) that lies near the supernova remnant (SNR) SN 1006 (cf. Fig. 1). In the radio-continuum domain, it shows a diffuse appearance, low surface-brightness (Milne 1971), and a globally uniform-and-intense polarization (Milne & Dickel 1974); however, there is no large-scale nebulosity in the optical domain (Green 2004). Despite its small angular separation from SN 1006 ( $\sim 2.4^\circ$ ), it is thought not to be associated with the supernova (SN) because it requires an unrealistically high mean expansion-velocity ( $\sim 0.1 - 0.5c$ ) (Milne 1971; Stephenson et al. 1977). The distance to the Lupus Loop ( $d_L$ ) is still uncertain: it varies from 0.17 kpc (Olano & Poppel 1981) to 0.5 kpc (Clark & Caswell 1976) and even to 1.2 kpc (Leahy et al. 1991).

The Lupus Loop region was studied in X-ray and radio, and the results showed a complex morphology surrounding the region. For example, Riegler et al. (1980) observed two enhanced 0.15 – 3.0 keV X-ray regions around the Lupus Loop. Colomb & Dubner (1982) observed two concentric H I shells and found that they are well-anticorrelated with the enhanced X-ray regions. (cf. Fig. 1).

The density of the ambient interstellar medium around the Lupus Loop ( $n_a$ ), the age ( $Y_L$ ) and the temperature ( $T_L$ ) of the Loop, and the initial total energy of the SN explosion ( $E_0$ ) were derived from several X-ray observations (Winkler et al. 1979; Gronenschild 1979; Toor 1980; Leahy et al. 1991):  $n_a$ , ranging from 0.02 to 0.1 cm<sup>-3</sup>, was somewhat low considering  $n_H = 0.07 - 0.5$  cm<sup>-3</sup>, the H I density at a similar galactic altitude (Dickey & Lockman 1990). Colomb & Dubner (1982)

also estimated  $n_a$  ( $\sim 0.13$  cm<sup>-3</sup>) from the column density of the inner H I shell. Estimates of  $Y_L$ , ranging from 20,000 to 50,000 yr based on the X-ray observations, are consistent with Milne's (1971) suggestion, based upon its diffuse appearance and low surface-brightness in radio, that the Lupus Loop is an old SNR. Estimates for  $T_L$  and  $E_0$  are on the order of 10<sup>6</sup> K and 10<sup>50</sup> – 10<sup>51</sup> erg, respectively.

We present in this paper the results of FUV emission line studies using the dataset from a new spectro-imaging observation of the Lupus Loop region. We focus on the spatial variation in the intensities of Si II\*  $\lambda 1533$  and C IV  $\lambda\lambda 1548, 1551$  emission lines and interpret the results in comparison with the features seen in infrared (IR) and X-ray images.

### 2. OBSERVATION AND DATA REDUCTION

The FUV observation was performed by *SPEAR*, also known as *FIMS*, aboard the first Korean Science and Technology SATellite, *STSAT-1*. The *SPEAR/FIMS* mission employs an imaging spectrograph which is optimized for the observation of the diffuse emission lines in the FUV domain. The L channel of the spectrograph covers 1350–1700 Å with a resolving power of  $\lambda/\Delta\lambda \sim 550$ . The field of view is  $7.4^\circ \times 4.3'$  with a 5–10' imaging resolution along the slit. The spectral half-energy line width, averaged over the angular field, is 3.2 Å. The instrument, its in-orbit performance, and the data analysis procedures are described in Edelstein et al. (2006).

The Lupus Loop region was observed during a sky survey between 6 May 2004 and 27 May 2004. Some of the observations were made with the shutter reduced to 10% of the full slit length. Overall the exposure time is 1 to 6 s. The detector dark background of  $0.03 \pm 0.01$  counts s<sup>-1</sup> Å<sup>-1</sup> was subtracted from the raw count rates. We followed the general analysis procedures described in Edelstein et al. (2006). As our concern is mainly the diffuse emission in and around the Lupus Loop, it is important to remove nearby bright point-sources. We have, therefore, excluded the pixels

Electronic address: jhshinn@kaist.edu

<sup>1</sup> Dept. of Physics, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea

<sup>2</sup> Space Sciences Laboratory, University of California, Berkeley, CA 94720, U.S.A.

<sup>3</sup> Korea Astronomy and Space Science Institute, 61-1 Hwaam-dong Yuseong-gu Daejeon, 305-348, Republic of Korea

of which the wavelength-averaged surface-brightness is greater than 8,000 CU ( $\text{CU} \equiv \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{\AA}^{-1}$ ; continuum unit). The criterion was set in view of the results of Schiminovich et al. (2001), in which the maximum intensity of a dust-scattered FUV-continuum was found to be about 5,000 CU near dust clouds and the Galactic plane. Spectra were created with 1.5 Å bin and then smoothed with a 4.5 Å-wide box-car to improve the signal-to-noise ratio of each bin.

For comparisons of our results in FUV observation with the features seen in X-rays and IR domain, which characterize the  $10^6$  K hot gas and cold dust, respectively, we have employed the archival data of the ROSAT All Sky Survey (RASS) maps (Snowden et al. 1995) and the Schlegel-Finkbeiner-Davis (SFD) 100  $\mu\text{m}$  IR map (Schlegel et al. 1998). These maps were extracted using the SkyView Observatory (McGlynn et al. 1998).

### 3. ANALYSIS AND RESULTS

We have divided the observed Lupus Loop region into four subregions based on the X-ray, IR, and  $\text{H}\alpha$  maps, as shown in Fig. 1. The core of Region-1 is occupied by hot gas, as seen in Fig. 1a of the RASS 1.5 keV map. The two H I shells identified by Colomb & Dubner (1982) surround Region-1, as indicated in Fig. 1a. Region 2 coincides, more or less, with the inner H I shell while Region-3, located inside the inner shell, shows the most intense X-ray in RASS 0.25 keV map. Region-4 is a test region for comparison with others. The SFD 100  $\mu\text{m}$  map (Fig. 1c) shows that Region-1 also includes dust near the northwestern boundary of the region. The same dust layer generally coincides with the inner H I shell in other parts. Hence, dust is also seen in Region-2. In Fig. 1d, it can be seen that  $\text{H}\alpha$  is prominent only around the hot gas in Region-1 and it diffuses away toward Region-2 and -3. As these maps indicate, hot gas coexists with cooler gas and dust in the broad region of Lupus Loop. Hence, we expect cooling processes to occur in their interaction regions. The purpose of the present work is to study such processes using the new FUV data obtained by *SPEAR/FIMS*.

Fig. 2 shows the total spectrum of all subregions in the 1380–1630 Å band. Some of the important atomic emission lines, such as N IV  $\lambda 1486$ , Si II\*  $\lambda 1533$ , and C IV  $\lambda\lambda 1548, 1551$ , are easily identified. The peak around  $\lambda 1409$  might represent the blending of the close O IV and S IV lines. Si II  $\lambda 1527$ , a companion of the doublet Si II\*  $\lambda 1533$ , is not seen in the spectrum. We believe it is due to the resonant scattering since Si II  $\lambda 1527$  is the transition to the true ground state and is likely to be optically thick in a neutral and warm ionized medium. It should be noted that the line was not detected in a similar study for the Orion-Eridanus superbubble (Kregenow et al. 2006). The spectrum also hints of the existence of molecular hydrogens.

In order to study the spatial variation of FUV emission characteristics, we have extracted the spectrum from each subregion around Si II\*  $\lambda 1533$  and C IV  $\lambda\lambda 1548, 1551$ , which represent  $10^4$  K and  $10^5$  K, respectively, and have estimated the intensities of these lines using a  $\chi^2$  minimization method (Kriss 1994). The Si II\* emission line was fitted with a single Gaussian profile while the C IV emission lines were fitted with two Gaussian profiles with their line ratio  $\lambda 1548 : \lambda 1551 = 2 : 1$ . The center wave-

lengths of the profiles were all fixed, and we assumed a linear continuum with its level as a free parameter. An extinction correction was made using the standard interstellar extinction curve (Cardelli et al. 1989, with  $R_V = 3.1$ ). We have used  $E(B - V) = 0.03$ , as derived by Crawford (2000) for the outflowing material from the Sco-Cen OB association (Crawford 1991; de Geus 1992), assuming this outflowing material resides in the line of sight toward the diffuse emission region of our concern. We believe this assumption is reasonable because the Lupus Loop region is located amid the angular coverage of the Sco-Cen OB association and the distance to the outflow region is only  $\sim 100$  pc (Crawford 2000) while that to the Lupus Loop is  $\gtrsim 170$  pc.

Fig. 3a–d show the spectra and fitting results for each subregion. It can be seen that Si II\* is prominent in Region-1 and -2 while its intensity decreases as we move from Region-2 to Region-3. There are no noticeable Si II\* or C IV lines in Region-4. We plot in Fig. 3e the estimated Si II\* and C IV line intensities for each subregion in LU ( $\equiv \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ ; line unit). Again, Si II\* is detected in Region-1 and -2 with 3- $\sigma$  confidence while C IV is detected with the same significance in Region-1, -2, and -3. The relative intensity ratio of C IV to Si II\* increases from Region-2 to Region-3, and neither of the lines is detected in Region-4 with 3- $\sigma$  confidence.

### 4. DISCUSSION

Based on the H I observations, together with the X-ray results, Colomb & Dubner (1982) conjectured that the Lupus Loop was formed by a supernova explosion inside a bubble of pre-existing stellar wind. Each of the two H I shells represents the boundary of the stellar wind and the supernova-shocked gas, respectively, while the stellar wind between the two H I shells and the innermost supernova-shocked gas are manifested as the regions of enhanced X-rays. The Lupus Loop region has been observed since then in other wavelength domains as well as in X-rays with higher spectral and spatial resolutions. Fig. 1 summarizes the recent observations of the region. The two RASS maps of Fig. 1 a and b, which represent 1.5 keV and 0.25 keV, respectively, indicate that the two hot gas regions may have different temperatures as Region-1 is brighter than Region-3 in the 1.5 keV map, while Region-3 is brighter than Region-1 in the 0.25 keV map. Following Snowden et al. (1997), in which the intensity ratios of the RASS bands are translated into the corresponding hot gas temperatures, we estimate the temperatures to be  $T_{R1} \sim 4.9 \times 10^6$  K and  $T_{R3} \sim 4.5 \times 10^6$  K while the associated uncertainties are large enough for the temperatures of these two regions overlap with each other. Fig. 1c, the SFD 100  $\mu\text{m}$  map, shows clumps of dust outside the outer H I shell and a rather broad layer along and just outside the inner H I shell. The upper left region of the figure is the Lupus Cloud, and the lower left corner merges into the galactic plane. On the other hand,  $\text{H}\alpha$  intensity, shown in Fig. 1d, generally decreases more or less monotonically from the galactic plane toward Region-4, except around the hot gas in Region-1. Region-4 is devoid of  $\text{H}\alpha$ . The region near the upper boundary of the figure also shows low  $\text{H}\alpha$  intensity where the IR map shows the existence of dust.

The present FUV study provides additional information to the features described above. In Region-1, where

both hot gas and dust exist, both Si II\* and C IV are detected with 3- $\sigma$  confidence. We believe the corresponding ionized Si originates from dust in this region through thermal evaporation by the hot gas or photo-ionization by the interstellar ultraviolet radiation field. Region-2, representing the inner H I shell, is the interface between the dust layer in Region-1 and the hot gas in Region-3, and both Si II\* and C IV are detected in this region with 3- $\sigma$  confidence. This is reasonable as they represent  $\sim 10^4$  K and  $\sim 10^5$  K gases, respectively. In Region-3, filled with hot gas and located farther away from the interface, it is natural that C IV, emanating from the cooling zone around the hot gas, is more prominent than Si II\*. In Region-4, neither Si II\* nor C IV is detected as this region is expected to be devoid of dust and mainly consists of tenuous hot gas.

It is worthwhile to note that a study similar to the present one has been conducted for the Orion-Eridanus Superbubble (Kregenow et al. 2006) using *SPEAR* data. Both Si II\* and C IV were found in their study from the thermal interface, at which H $\alpha$  also peaked. On the other hand, H $\alpha$  does not show a notable feature in the interface region, Region-2 and -3, in the present case. Colomb & Dubner (1982) estimated the expansion velocity of the inner H I shell to be  $23 \pm 3$  km s $^{-1}$ , which corresponds to the post-shock temperature of  $T_{ps} = 3\mu m_H V_s^2 / 16k \simeq 1.2 \times 10^4$  K, where  $\mu$  is the molecular mass in units of the hydrogen atom mass ( $m_H$ ). Considering the ionization energies of Si $^+$  and H $^+$ , 8 eV

and 14 eV, respectively, this low temperature might explain the absence of prominent H $\alpha$  while Si II\* can still be detected.

## 5. SUMMARY

Using the new FUV dataset obtained from *SPEAR/FIMS*, we have studied the spectral characteristics of the Lupus Loop region. Our result shows that Si II\* and C IV emission lines emanate from the interface between the hot gas and the cooler H I shell with which a dust layer is also associated. Si II\* is more prominent closer to the region while C IV farther away from it. This result is consistent with other observations in X-rays, IR, and radio, each of which shows distinctive features. The interface is rather broad and a shock, whose structure is not clear in the FUV result, should have a very low velocity if it exists.

*SPEAR/FIMS* is a joint project of the Korea Advanced Institute of Science and Technology, the Korea Astronomy and Space Science Institute, and the University of California at Berkeley, funded by the Korea Ministry of Science and Technology and the U.S. National Aeronautics and Space Administration Grant NAG5-5355. The authors appreciate Dubner for providing the H I image. They are also grateful for valuable suggestions of the referee. Some of the results in this paper have been derived using the HEALPix (Górski et al. 2005) package.

## REFERENCES

- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245  
 Clark, D. H. & Caswell, J. L. 1976, *MNRAS*, 174, 267  
 Colomb, F. R. & Dubner, G. 1982, *A&A*, 112, 141  
 Crawford, I. A. 1991, *A&A*, 247, 183  
 —. 2000, *MNRAS*, 317, 996  
 de Geus, E. J. 1992, *A&A*, 262, 258  
 Dickey, J. M. & Lockman, F. J. 1990, *ARA&A*, 28, 215  
 Edelstein et al. 2006, *ApJ*, this volume, *SPEAR* instrument paper  
 Finkbeiner, D. P. 2003, *ApJS*, 146, 407  
 Górski et al. 2005, *ApJ*, 622, 759  
 Green, D. A. 2004, *Bulletin of the Astronomical Society of India*, 32, 335  
 Gronenschild, E. H. B. M. 1979, *A&A*, 77, 53  
 Kregenow et al. 2006, *ApJ*, this volume  
 Kriss, G. 1994, in *ASP Conf. Ser. 61: Astronomical Data Analysis Software and Systems III*, 437  
 Leahy, D. A., Nousek, J., & Hamilton, A. J. S. 1991, *ApJ*, 374, 218  
 McGlynn, T., Scollick, K., & White, N. 1998, in *IAU Symp. 179: New Horizons from Multi-Wavelength Sky Surveys*, 465  
 Milne, D. K. 1971, *Australian Journal of Physics*, 24, 757  
 Milne, D. K. & Dickel, J. R. 1974, *Australian Journal of Physics*, 27, 549  
 Olano, C. A. & Poppel, W. G. L. 1981, *A&A*, 94, 151  
 Riegler, G. R., Agrawal, P. C., & Gull, S. F. 1980, *ApJ*, 235, L71  
 Schiminovich, D., Friedman, P. G., Martin, C., & Morrissey, P. F. 2001, *ApJ*, 563, L161  
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525  
 Snowden, S. L., Egger, R., Freyberg, M. J., McCammon, D., Plucinsky, P. P., Sanders, W. T., Schmitt, J. H. M. M., Truemper, J., & Voges, W. 1997, *ApJ*, 485, 125  
 Snowden, S. L., Freyberg, M. J., Plucinsky, P. P., Schmitt, J. H. M. M., Truemper, J., Voges, W., Edgar, R. J., McCammon, D., & Sanders, W. T. 1995, *ApJ*, 454, 643  
 Stephenson, F. R., Clark, D. H., & Crawford, D. F. 1977, *MNRAS*, 180, 567  
 Toor, A. 1980, *A&A*, 85, 184  
 Winkler, P. F., Hearn, D. R., Richardson, J. A., & Behnken, J. M. 1979, *ApJ*, 229, L123

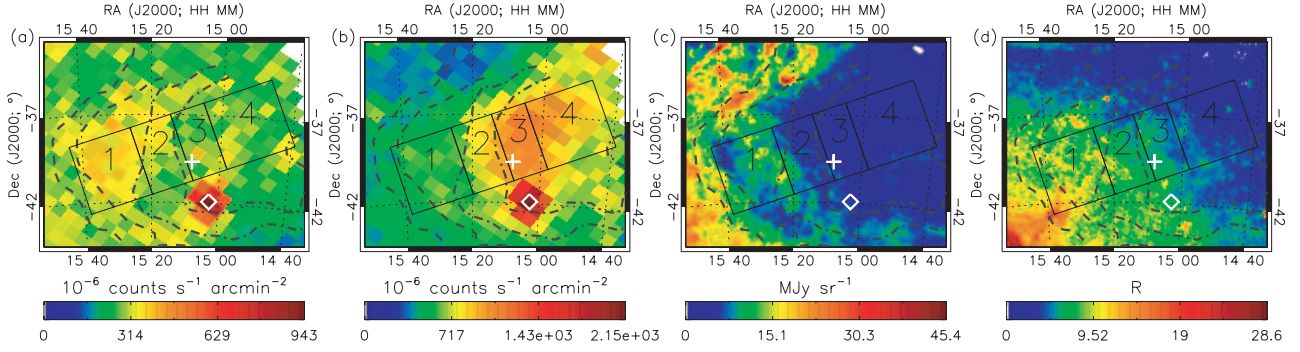


FIG. 1.— The Lupus Loop region in different wavelengths. We select four subregions based on these images in different wavelength domains. The two dash-dotted curves and the dashed curves represent the boundaries of the inner and outer H I shells identified by Colomb & Dubner (1982), respectively. The maps are centered at  $\alpha = (15^h 20^m 0.0^s, \delta = -37^\circ 30' 0.0'')$  in J2000. ‘ $\diamond$ ’ and ‘+’ indicate SN 1006 and the projected center of the Lupus Loop, respectively. (a) Rosat All Sky Survey (RASS) 1.5 keV map (Snowden et al. 1995), (b) RASS 0.25 keV map (Snowden et al. 1995), (c) Schlegel-Finkbeiner-Davis (SFD) 100  $\mu\text{m}$  map (Schlegel et al. 1998), and (d)  $\text{H}\alpha$  map (Finkbeiner 2003)

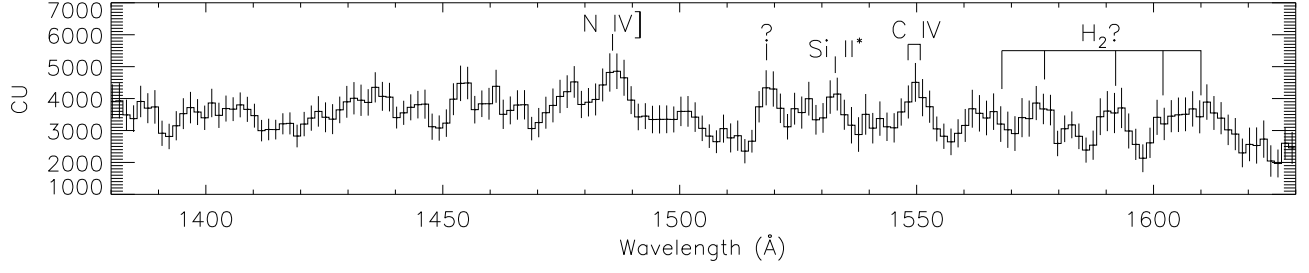


FIG. 2.— Identification of emission lines in the total spectrum. The total spectrum of all subregions, binned in 1.5 Å, is smoothed with a box-car whose width is  $3 \times (\text{bin size})$ . Si II\*  $\lambda 1533$ , C IV  $\lambda\lambda 1548, 1551$ , and N IV]  $\lambda 1486$  are identified.

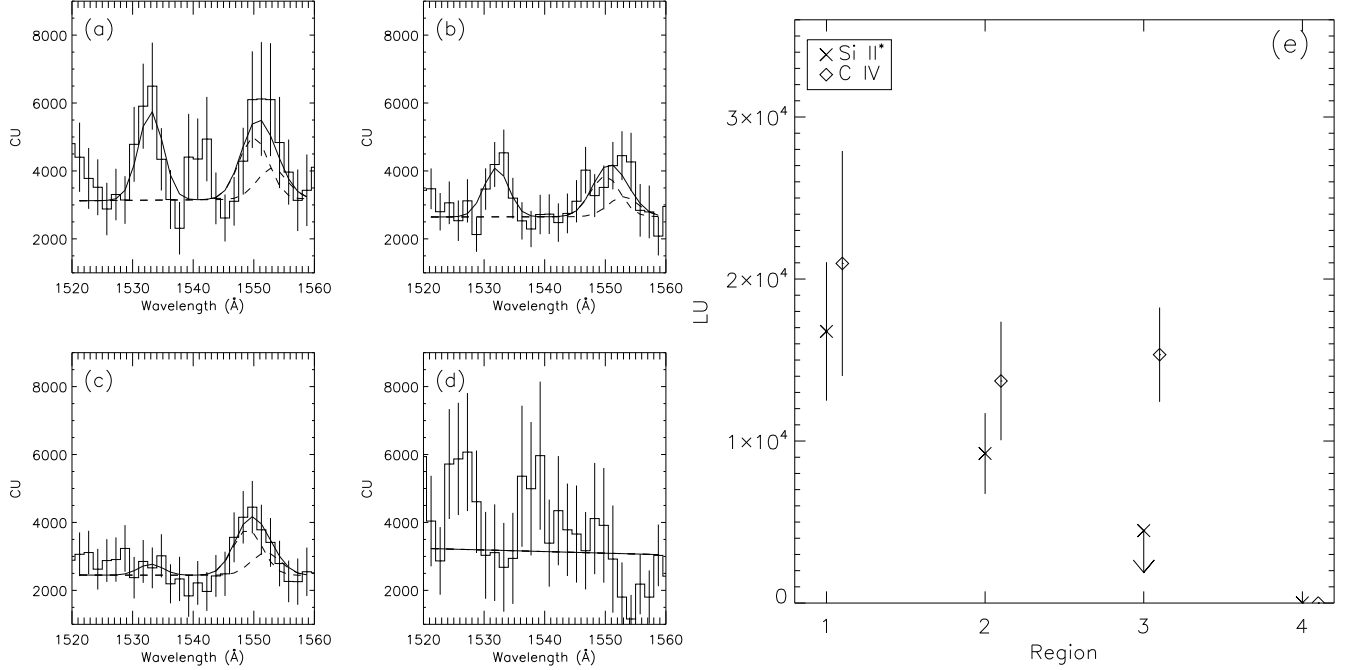


FIG. 3.— Fitting of Si II\*  $\lambda 1533$  and C IV  $\lambda\lambda 1548, 1551$  for each subregion. The histogram, solid-line, and dashed-line in (a)–(d) represent the L-channel spectrum with 1- $\sigma$  error bar, fitting lines, and the two components of C IV  $\lambda\lambda 1548, 1551$  fitting lines, respectively. In (e), where the line intensities of Si II\* and C IV are shown for each subregion, the C IV mark is slightly shifted to the right to avoid the overlapping of the 1- $\sigma$  error bar. Si II\* in Region-3 and -4 are given with 90% upper limits, as indicated by arrows. No acceptable fitting was found for both Si II\* and C IV in Region-4 with finite intensity.